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To whom it may concern

Review of the PhD thesis
"Influence of Charge Formation Mechanism on the Structure of Electrohydrodynamic Flow in Highly Non-Uniform Electric Field"
submitted by Vladimir Chirkov as a requirement for the scientific degree of Doctor of Philosophy in Physics at the St. Petersburg State University

The PhD thesis "Influence of Charge Formation Mechanism on the Structure of Electrohydrodynamic Flow in Highly Non-Uniform Electric Field" has been submitted by Mr. Vladimir Chirkov as a requirement for the scientific degree of Doctor of Philosophy in Physics at the St. Petersburg State University.

The thesis concerns electrohydrodynamic (EHD) flows caused by the interaction of the electric field and the electric space charge in low-conducting liquids when the electric current passes through them. This subject is of a high interest because the EHD flow plays an important role in the electric conductivity of dielectric liquids. Therefore, the investigations of EHD processes in dielectric liquids are crucial for development and improvement of various devices the operation of which is based or depends on the electric current flow through dielectric liquids. EHD pumps, heat exchangers, atomizers and filters are examples of such EHD flow-based devices. The EHD phenomena in dielectric liquids are still far from being quite elucidated. Therefore, the study undertaken by Mr. Chirkov on the electric charge formation and its influence on the patterns of EHD flow in dielectric liquids, in which a highly non-uniform electric field exists, is of the present interest.

The dissertation and the attached 4 papers present original results of the investigations of the EHD flow and electric current in low-conducting liquids. Since the both phenomena are complicated, the Author's research method is two-folded: he applied a numerical simulation and an experimental study. The majority of his research concerns the EHD and electric phenomena occurring in the needle–plane electrode system in dielectric liquids, where the electric field is highly non-uniform, whereby the near-electrode processes of electric charge formation are considerably enhances even at a relatively low applied voltage.

The dissertation submitted for reviewing consists of 51 pages and copies of 4 peer-reviewed papers, of which Mr. Chirkov is a co-author. These papers were published in 2008–2013 in the following international journals: Technical Physics, Surface Engineering and Applied Electrochemistry, and Journal of Electrostatics.

The dissertation consists of an Abstract, Introduction, Main part describing the simulation method used by the Author, experimental technique and results, Conclusions, and References.

The Introduction provides comprehensive information on the background of the electrohydrodynamics in dielectric liquids, describes previous studies including the achievements of Prof. Y. Stishkov's group, to which the Author of the dissertation belongs, and briefly presents the goal and results of the PhD studies carried out by the Author. In the Main part the Author presents his own results of the numerical simulation of EHD flow structures in dielectric liquids for various models of the electric charge formation, i.e. for the injection into non-conducting and low conducting liquids and for the field-enhanced dissociation. The Main part of dissertation shows also results of the experimental studies carried out by the Author. They concern the current–voltage and transient current characteristics in dielectric liquids. Then the Author presents comparison of the numerical simulation results with the experimental, and describes features of the EHD flow in the strong electric field in dielectric liquids. The Main part ends with the Conclusions. Each subsection of the Main part is a brief summary of the results published by the Author in peer-reviewed papers. It helps to understand the framework of the Author's research. The details can be found in the original papers.

The thesis provides results of the numerical and experimental investigations of EHD flows in low-conducting liquids on the base of transformer and petrolatum oils, having the electric conductivity between 10^{-13} and 10^{-7} S/m. The investigations were focused on the EHD flow kinematics, electric force and electric current structures under the injection and dissociation mechanisms of charge formation. The numerical studies gave the deep insight into the high-voltage processes related to the current passage through dielectric liquids in a wide voltage range (up to the breakdown) in different cases of the charge formation: injection into non-conducting liquid, dissociation without injection, injection into low-conducting liquid and field-enhanced dissociation. The experimental investigations mainly served to deliver experimental data for verifying the numerical results and to validate the choice of various calculation parameters.

In my opinion the most important achievements and findings of the thesis are as follows:

- A new approach to the computer simulation of EHD flows in liquids with a non-zero conductivity on the basis of the complete set of EHD equations;
- A new approach to the calculation of the integral current characteristics, which takes into account both the surface and bulk space charge formation and the dependence of the dissociation rate on the electric field strength;
- Analysis of the transient mode of the EHD flow formation after applying the pulsed voltage application under the injection and dissociation mechanisms of charge formation;
- Explanation of the EHD flow instabilities in the case of strong injection mechanism;
- Analysis of the prevailing mechanism of charge formation (the injection and dissociation) in the EHD flows in low-conductivity liquids. Defining the conditions for the prevailing mechanism;
- Defining the EHD flow structures for each of the charge formation mechanisms;
- A method for the numerical calculation of the transient current characteristics and dynamical current-voltage characteristics with taking into account the convective and migration mechanisms of charge transport and the Wien effect;
- Defining the role of EHD flows on the electric characteristics for each charge formation mechanism;
- Explanation of the experimentally-found EHD flow structures basing on the energy transformation analysis.

It is worth noting that although the finite-element method employed in the work is widely used by others, there are also other methods applicable for solving the complete set of EHD equations, for example the finite-volume, particle-in-cell and flux corrected transport methods. The Author of the thesis justified the use of finite-element method in the Introduction, showing pro and contra arguments of his choice. The quite high validity of the numerical results and satisfactory qualitative and quantitative agreement between the experimental data and computer simulation can be considered as positive verification of the numerical method chosen by the Author.

In my opinion there are several minor shortcomings in the dissertations. They are:

- The Authors did not tackle the problem of influence of the dielectric liquid properties on the numerical simulations of the EHD structures;
- It is not clear if the numerical calculations cover also the case when at higher voltages the electric discharge occurs in the liquid;
- It is not clear if the axisymmetrical model used in the thesis is valid for the case of the strong injection when instabilities of EHD flows takes place. How can the corresponding results presented in the included article PII be interpreted?
- Using the commercial software for the numerical simulations unabled the Authors to change discretization schemes, usually highly needed at the needle tip. As a consequence the Author had to increase the value of the diffusion coefficient to obtain a stable solution of the calculation process. How does such a procedure influence the credibility of the results?
- Regarding the experimental studies, how did the impurity of the liquids used in the experiment influence the results?
- Also, how does the liquid impurity due to seeding particles used for either Particle Tracking Velocity or Particle Image Velocimetry influence the electrical behavior of the liquid?

The results of Mr. Chirkov's research significantly contributed to the development of electrohydrodynamics. He simulated the EHD flows under different mechanisms of charge formation. The performed numerical experiments clarified the role of the injection and dissociation mechanisms in the presence of EHD flows. The numerical results are new and interesting for the specialists. The proposed simulation technique is a useful tool for designing those EHD devices in which the dissociation and recombination processes in the bulk play an important role. The experimental method used by the Author was sufficient for verifying the numerical results and validate the choice of various calculation parameters. However, it could not deliver very sophisticated experimental results.

In my opinion the quality and quantity of the scientific material presented by the Author are sufficient to meet requirements of a dissertation. The quality of the Author's papers included into his dissertation was verified by reviewers of the international journals in which Mr. Chirkov published the papers. Mr. Chirkov is a coauthor of many other papers which he has not included into the dissertation, although referring to them (e.g., AI and AIII).

I know scientific activity of Mr. Chirkov from several international conferences in which he participated. At these conferences he presented several contributions, showing to the audience his deep knowledge of the electrohydrodynamics. The presentations of Mr. Chirkov were always received very well.

Summarizing my review, I would like to confirm my very positive opinion about the results presented by Mr. V. Chirkov in his dissertation. I believe that also the EHD society would share my opinion. The scientific research activity of Mr. V. Chirkov becomes known and appreciated by that society. The scientific works carried out by Mr. V. Chirkov are important not only for understanding the fundamentals of electrohydrodynamics in low-conducting liquids physics but they are practical and may be implemented for the development of EHD devices. Since the thesis fully fulfills the requirements commonly

accepted for awarding the degree of Doctor of Philosophy in Physics, I strongly support the procedure leading towards awarding Mr. V. Chirkov with this degree.

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